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# New food compositions to increase the content of phenolic compounds in extrudates

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**Abstract:** Phenolic compounds are linked to a number of health benefits, including antioxidant, antibacterial, antiglycaemic, antiviral, anticarcinogenic, anti-inflammatory and vasodilatory properties. To improve a great loss of phenolics during extrusion, researchers have investigated incorporating functional ingredients into the extrusion input mixture. Other reasons for the addition of active ingredients are the re-use of by-products from food technology, decreasing the calorie content of extruded food, inhibition of starch digestion, and the colour change of the gluten-free products. The paper presents 28 examples of new designs for extrusion based on rice, corn, cassava, sorghum, and lentil flours and on other crops, together with the analyses of phenolics. The present results show the highest total phenolic content in sorghum among cereals, and lentil flour and orange peel powder among mixtures for extrusion to prepare extrudates. The highest content of total flavonols was found in the mixture containing corn and freeze-dried red and purple potatoes.

**Keywords:** thermal processing; rice; sorghum; extrusion; phenolic acids; flavonols

Phenolic compounds are an internal physiological regulator in plants. They also affect the growth hormone auxin indole-3-acetic acid (IAA). Additionally, phenolic compounds are responsible for the protection of plants from sunlight by absorbing short high-energy wavelengths. They can also protect the plants from insects and serve as an attractant for pollinators.

Phenolic compounds can be released from the food matrix in the gastrointestinal tract by enzymes and pH conditions. The released free phenolics are absorbed in the small intestine, followed by conjugation with other compounds, leading to their introduction into the blood circulation system. In recent years, a variety of bioactivities of phenolic acids have been reported such as anti-cancer activity, inhibitory activity against hepatitis C virus, anti-bacterial and anti-viral properties, mitigation of angina pectoris and hypertension, effectivity against diabetes, cardiovascular disease, and neurodegenerative disease (Shahidi & Yeo 2016).

An extrusion process modifies the functional properties of ingredients and texturises them. Short-time processing gives a potential advantage for retaining phenolics compared to other heat treatments (Xu et al. 2017) but some authors found a great loss (> 50%) of phenolics during extrusion (e.g. Repo-Carrasco-Valencia 2009; Altan et al. 2009). Thus, researchers have investigated the improving of the nutritional profile of extruded products by functional ingredients such as fruits, vegetables, or edible by-products (Shevkani et al. 2019; Zeng et al. 2019). Extrusion has also been reported to increase the total amount of bound phenolics while decreasing the free ones (Sarawong et al. 2014). In addition, because sensory properties of extrudates are important, it is necessary to seek suitable composition of the input mixture and optimal parameters of the extrusion process.

Common reasons for the use of extrusion to process bioactive mixtures are:

- high content of nutritional substances such as vitamins or phenolics
- re-use of by-products (wastes) from food technology
- decrease of the calorie content of the extruded food and inhibition of starch digestion
- change in the colour of the product
- gluten-free products.

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## EXTRUSION BASED ON RICE BLENDS

**Extrusion of the mixture containing rice and goji berries.** In traditional medicine, goji berries are the remedy for diminished vision function, infertility, abdominal pain, dry cough, and headache (Potterat 2010). Kosinska-Cagnazzo et al. (2017) investigated extrudates based on rice flour and goji berries using a twin-screw extruder with constant feed moisture (FM) and a screw speed (SS) of 400 rpm. The barrel of 40D (diameter of the extruder) in length (L) was heated in temperature zones of 20, 40, 60, 80, and 100 °C; the last temperature was set to 110, 130 or 150 °C. The total phenolic compounds (TPC) in the extrudates are surveyed in Table 1.

Decomposition of heat-labile phenolic compounds and polymerisation of some phenolic compounds during extrusion tend to decrease the extractable phenolic content. On the other hand, due to the disruption of cell wall matrices and the breaking of high molecular weight complex phenolics during extrusion, the extractability of phenolic compounds is improved (Wang et al. 2014).

**Extrusion of the mixture containing rice and yellow pea flour to produce gluten-free precooked pasta.** Bouasla et al. (2016) produced gluten-free precooked pasta from a rice/yellow pea flour blend (2 : 1) using a TS-45 single-screw extrusion-cooker (ZMCh Metalchem, Gliwice, Poland). The final section of the extruder was cooled down so that the temperature of the product exciting the die would not exceed 100 °C, as this prevents the formation of the porous structure and reduces pasta stickiness. The effect of moisture content and SS on some quality parameters were assessed. The phenolic acid profile was analysed by high-performance liquid chromatography-electrospray ionisation tandem mass spectrometry (Table 2) and selected pasta properties, including sensory acceptability, were tested. The extrusion-cooking process at 30% of FM with 80 rpm seemed to be appropriate to obtain precooked pasta with a high content of phenolics.

**Extrusion of the mixture containing brown rice and pomelo peel.** Whole grain brown rice has potential health benefits due to its high content of dietary fibre, phenolics, phytoestrogens, vitamins, and minerals. However, the phenolic compounds of brown rice are significantly decreased after extrusion (Zeng et al. 2019). Pomelo contains carotenoids, anthocyanins and other phenolics, vitamin C and lycopene; additionally, pomelo rind and pith are rich in pectin. Shi et al. (2017) used a single-screw extruder (Northern Finance Ltd, Auckland, New Zealand; screw length 30 cm, screw diameter 30 mm) through a 3 mm die face. The outer layers of the pomelo were removed; the peel included the outer waxy layer and the pithy sublayer. The peel was oven-dried at 50 °C, and 5, 10, and 15% inclusion of brown rice was prepared. The temperature at the die (TD) was 180 °C; SS of 200 rpm was maintained during the process with a feed rate (FR) of 9 kg $h^{-1}$. The pomelo rind inclusion increased the antioxidant activity of the extrudates. TPC were from 8.4 to 16.1 mg 100 $g^{-1}$ DS, depending on the content of pomelo rind (Table 1).

**Extrusion of the mixture containing rice, oat, corn flour and olive pomace.** Oat (*Avena sativa*) has a large amount of different dietary fibre components of mixed-linkage (1–3), (1–4) β-D-glucan, cellulose and arabinoxylans. It is also a good source of antioxidants such as vitamin E, phytic acid, phenolic acids and avenanthramides (Wani & Kumar 2016a). Ying et al. (2017) worked with a co-rotating twin-screw extruder. The two base formulations before the addition of olive powder contained oat flour (20%), corn or rice flour (78.5%), calcium carbonate (1%) and sodium chloride (0.5%). The addition of olive pomace fractions reduced the die pressure and specific mechanical energy during extrusion and resulted in lower radial expansion in the extruded product. FR, SS and die diameter (DD) were approximately 2.5–2.6 kg $h^{-1}$, 500 rpm and 3.0 mm, respectively. The retention of polyphenols during extrusion was about 63–75% (Table 1).

**Gluten-free formulations based on beans, carob fruit and rice.** Beans provide proteins, essential fatty acids, complex carbohydrates, vitamins and minerals in the diet of many people; their consumption is associated with a reduced risk of cancer and heart disease. These effects might be related to the presence of some phenolic compounds (Espinoza-Moreno et al. 2016). Carob fruit is a source of soluble saccharides, which leads to its use in sweets as a natural food additive, as a thickening agent (E-410), and as a stabiliser and flavouring agent. Carob flour is a good source of dietary fibre; it has been shown to have therapeutic potential for reducing LDL (low density lipoprotein) cholesterol, regulating blood glucose levels, and benefitting the body weight (Valero-Munoz 2014). Therefore, it could be a novel ingredient to be used for functional food products. Arribas et al. (2019) processed mixtures (rice: 50–80%, beans: 20–40% and carob: 5–10%) using a Clextral Evolum 25 twin-screw extruder (Clextral, Firminy, France). The screw diameter (SD) was 25 mm and the screw length was 600 mm; the capacity of 25 kg feed $h^{-1}$ by 900–950 rpm was used, having

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Table 1. Total phenolic compounds in extrudates from chosen mixtures

| Source | Source input (raw material) (mg 100 g$^{-1}$ DS) | Output (mg100 g$^{-1}$ DS) | Retention (%) | Extruder | Author |
|---|---|---|---|---|---|
| Rice/goji berries | 123–402 | 51–741 | 41–184 | twin-screw | Kosinska-Cagnazzo et al. (2017) |
| Brown rice/pomelo | – | 8.4–16.1 | – | single-screw | Shi et al. (2017) |
| Rice/maise-oat flour with 5% of olive pomace | – | 20–161 | 63–75 | co-rotating twin-screw | Ying et al. (2017) |
| Rice/beans/carob fruit | 10–77 | 0.2–16.7 | 2–97 | twin-screw | Arribas et al. (2019) |
| Broken rice/açaí | 188–500 | 104–279 | 51–56 | single-screw | Ribeiro Oliveira et al. (2019) |
| Brown rice / *Choerospondias axillaris* | – | 56–140 | – | twin–screw | Zeng et al. (2019) |
| Brown rice/ straw mushrooms | – | 91–152 | – | co-rotating twin-screw | Tepsongkroh et al. (2019) |
| Corn/chickpea/spinach | – | 44–70 | – | co-rotating twin-screw | Shevkani et al. (2019) |
| Corn flour/sorghum flour/ apple pomace | 123–172 | 58–126 | 60–70 | single-screw | Lohani & Muthuku-marappan (2017) |
| Corn/carrot | 1 820 | 950–1 030 | 52–57 | co-rotating twin-screw | Ortak et al. (2017) |
| Genetically modified corn & bean kernels | 140 | 244 | 174 | single-screw | Espinoza-Moreno et al. (2016) |
| Corn/purple potato | – | 155–259 | – | single-screw | Gumul et al. (2018) |
| Corn/red potato | – | 157–418 | – | single-screw | Gumul et al. (2018) |
| Corn/buckwheat | – | 75–100 | – | co-rotating twin-screw | Singh et al. (2019) |
| Cassava flour/ tigernut flour | 670–990 | 510–940 | 71–108 | single-screw | Adebowale et al. (2017) |
| Cassava/soy/ grape pomace | 210–770 | 90–590 | 43–77 | co-rotating twin-screw | Oladiran & Emmambux (2018) |
| Lentil flour/yeast | 48–83 | 4–8 | 6–10 | co-rotating twin-screw | Ciudad-Mulero et al. (2018) |
| Lentil flour/orange peels powder | 4 685 | 3 285–4 038 | 70–86 | co-rotating twin-screw | Rathod & Annapure (2017) |
| Wheat/dried artichoke | 340 | 220 | 65 | co-rotating twin-screw | Guven et al. (2018) |
| Sorghum/roasted coffee | 139–424 | 124–590 | 60–148 | single-screw | Chávez et al. (2017) |
| Meat analogues based on *Spirulina*/lupin protein | 333–691 | 438–847 | 94–109 | twin-screw | Palanisamy et al. (2019) |
| Soybean | 540 | 652–660 | 120–122 | twin-screw | Azad et al. (2019) |
| Soy/wheat gluten/ corn starch/green tea | 3847–5749 | 1 522–3 160 | 39–55 | co-rotating twin-screw | Ma & Ryu (2019) |

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2.5–4 kg $h^{-1}$ water addition. The extrusion temperature 120–130 °C did not cause an increase in TPC (Table 1).

**Pregelatinised flours from broken rice grains combined with lyophilised açaí pulp.** Açaí (*Euterpe oleracea*) is a fruit from the Amazon, and its pulp is considered to be a source of fibre, lipid, bioactive compounds, minerals, and protein (Rufino et al. 2011). In order to obtain the pregelatinised flours, Ribeiro Oliveira et al. (2019) processed the materials in a single-screw extruder (Imbramaq, Ribeirao Preto, Brazil), with three barrel constant heating zones (41, 61, and 84 °C), a helical grooved extrusion sleeve, and a 4 mm matrix diameter. The extrusion changed the absorption of water and the pasting properties of the pregelatinised flours. It also affected the colour and chemical composition, significantly the anthocyanin content, TPC (Table 1) and the antioxidant capacity, despite the mild process conditions.

**Extrusion of rice, corn, dried green pea, oat, and fenugreek seed flours and fenugreek leaf powder.** Antidiabetic, anticarcinogenic, hypocholesterolaemic, immunological activity, antioxidant and antibacterial properties are found in fenugreek (*Trigonella foenum-graecum*) (Wani & Kumar 2016b). Wani and Kumar (2016a) used a twin-screw extruder (Basic Technology Pvt. Ltd., Kalkata, India) to prepare extruded snacks. DD, temperature and moisture were 4 mm, 110 °C and 12% (wb), respectively. The materials used in the study include dried green pea flour, oat flour, fenugreek seed flour (FSF), fenugreek leaf powder (FLP) and a composite flour of rice and corn (80 : 20). In order to maximise the beneficial effects of FSF and FLP, a maximally 1.3% level of FSF and FLP was found to be suitable for the development of extruded snacks. The antioxidant activity, total phenolic content, protein and fibre content were found to be higher at higher concentrations of active ingredients (FSF and FLP).

**Extrusion of the mixture containing brown rice and *Choerospondias axillaris*.** *Choerospondias axillaris* is a traditional Chinese medicinal plant. A large quantity of peels is a by-product of juice or pastille production, usually discarded as waste. It is rich in phenolic compounds identified as phenolic acids, flavonoids, and flavonoid glycosides, in which the most abundant compounds were found to be (+)-catechin and dimers of procyanidins (Li et al. 2015). Especially, their extracts have antioxidant, antiproliferative, and antiangiogenic activity, as well as the ability to inhibit starch digestion. Zeng et al. (2019) investigated the physicochemical properties of extruded brown rice with the addition of 1–10% *Choerospondias axillaris* fruit peels by a twin-screw extruder (DS32-I; Saixin Machinery Co., China). The barrel temperature of the feeding zone and two extrusion zones, SS and FR, were set at 60, 80, and 100 °C, 50 rpm and 10 kg $h^{-1}$, respectively. Phenolics of the extrudates (Table 1) were positively correlated with the addition.

**Extrusion of the mixture containing brown rice and straw mushrooms.** Tepsongkroh et al. (2019) prepared brown rice-based extrudates containing straw mushrooms by a co-rotating twin-screw extruder (ZE 25 × 33D; Hermann Berstorff Laboratory, Hannover, Germany) which consisted of 7 sections ending with a 24.5 mm thick die plate and one wavy chip-shaped (1 mm × 20 mm) die hole. FR was controlled at 4.8 kg $h^{-1}$ and SS was set at 350 rpm. Increasing mushroom powder content (MP) from 0 to 20% resulted in increased density, TPC (Table 1) and antioxidant activity, while increasing FM from 13 to 19% resulted in increased density and texture hardness. The optimal conditions for producing nutritious snacks were at 13–14% FM and 14–17% MP.

## EXTRUSION BASED ON CORN BLENDS

**Extrusion of the mixture containing corn grits, chickpeas and spinach.** Corn grits are a major constituent of extruded products. Spinach is a green vegetable having high total dietary fibre and essential minerals like K, Mg, Na, Ca, Cu, and Fe (Singh et al. 2016). It also contains biologically active phytochemicals, such as carotene, phenolic acids, flavonoids and fatty acid derivative compounds having anticarcinogenic, antimicrobial and antioxidant activity. Chickpeas contain high amounts of high-quality protein, complex carbohydrates, dietary fibre, folate and essential minerals. Shevkani et al. (2019) performed an extrusion process on a co-rotating and intermeshing twin-screw extruder (BC 21; Clextral, France) at the constant moisture, temperature and SS of 16%, 150 °C and 500 rpm, respectively. Barrel diameter and its L/SD were 25 mm and 16 : 1, respectively, while DD was 6 mm. TPC ofthe extrudates increased with the increased incorporation of chickpeas (CP) and spinach (SP). Sensory analysis revealed that CP and SP at the respective incorporation levels of 25% and 4% could be blended with corn grits for a highly acceptable expanded snack.

**Extrusion of the mixture containing corn flour, sorghum flour and apple pomace.** Sorghum is gluten-free and has the highest content of phenolics among cereals, especially phenolic acids, flavonoids and tannins (de Morais Cardoso et al. 2015; Awika & Rooney 2004). Apple pomace is a source of phytochemicals

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Table 2. Phenolic acids in extrudates from chosen mixtures

| Phenolic acid | Source | Source input (raw material) (mg 100 g$^{-1}$ DS) | Output (mg 100 g$^{-1}$ DS) | Retention (%) | Author |
|---|---|---|---|---|---|
| Ferulic acid | Rice/pea | – | 1.2–3.4 | – | Bouasla et al. (2016) |
| Ferulic acid | Corn flour/ sorghum flour/ apple pomace | 4–5 | 2.5–3.5 | 71–76 | Lohani & Muthuku-marappan (2017) |
| Ferulic acid | Corn/kale | – | 0.2–4.6 | – | Kasprzak et al. (2018) |
| *p*-Coumaric acid | Rice/pea | – | 0.03–0.08 | – | Bouasla et al. (2016) |
| *p*-Coumaric acid | Corn/red potato | – | ND–0,4 | – | Gumul et al. (2018) |
| *p*-Coumaric acid | Corn flour/ sorghum flour/apple pomace | 1,0–1,5 | 0.5–0.9 | 46–63 | Lohani & Muthuku-marappan (2017) |
| *p*-Coumaric acid | Corn/kale | – | 0.13–0.17 | – | Kasprzak et al. (2018) |
| Protocatechuic acid | Corn/kale | – | 0.005–0.019 | – | Kasprzak et al. (2018) |
| Protocate-chuic acid | Rice/pea | – | ND–0.04 | – | Bouasla et al. (2016) |
| Protocatechuic acid | Corn flour/ sorghum flour/apple pomace | 2–5 | 0.2–1.6 | 10–29 | Lohani & Muthuku-marappan (2017) |
| 4-OH-Benzoic acid | Rice/pea | – | 0.03–0.07 | – | Bouasla et al. (2016) |
| 4-OH-Benzoic acid | Corn flour/ sorghum flour/apple pomace | 1.7–2.3 | 1.1–1.7 | 63–71 | Lohani & Muthuku-marappan (2017) |
| 4-OH-Benzoic acid | Corn/kale | – | 0.01–0.03 | – | Kasprzak et al. (2018) |
| Salicylic acid | Rice/pea | – | 0.03–0.08 | – | Bouasla et al. (2016) |
| Salicylic acid | Corn flour/ sorghum flour/apple pomace | 5–7 | 3–5 | 67–74 | Lohani & Muthuku-marappan (2017) |
| Salicylic acid | Corn/kale | – | 0.02–0.04 | – | Kasprzak et al. (2018) |
| Caffeic acid | Corn flour/ sorghum flour/apple pomace | 5.0–5.7 | 4.2–4.9 | 84–86 | Lohani & Muthuku-marappan (2017) |
| Caffeic acid | Corn/kale | – | 0.03–0.05 | – | Kasprzak et al. (2018) |
| Caffeic acid# | Corn/ dragonhead leaves | – | 23–60 | – | Wojtowicz et al. (2017) |
| Chlorogenic acid | Corn flour/ sorghum flour/apple pomace | 0.3–0.8 | 0.05–0.3 | 15–38 | Lohani & Muthuku-marappan (2017) |
| Vanillic acid | Corn/kale | – | 0.08–0.11 | – | Kasprzak et al. (2018) |
| Sinapic acid | Corn/kale | – | 0.6–1.3 | – | Kasprzak et al. (2018) |
| Rosmarinic acid | Corn/ dragonhead leaves | – | 287–2 884 | – | Wojtowicz et al. (2017) |
| Cynarin and cynaroside | Wheat/dried artichoke | 1.8–5.4 | 0.6–1.3 | 25–34 | Guven et al. (2018) |

ND – not detected

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such as antioxidants and dietary fibre. Lohani & Muthukumarappan (2017) extruded a blend of corn flour, hydrodynamic cavitated sorghum flour and apple pomace to investigate the effect of extrusion processing on TPC along with some selected textural and functional properties. They tested three levels of apple pomace ratio APR (10, 20, and 30%), FM (25, 30, and 35% wb), TD (80, 110, and 140 °C) and SS (100, 150, and 200 rpm). The extrusion experiments were carried out on a single-screw extruder (Model PL 2000; Brabender Plasti-Corder, South Hackensack, NJ, USA). The extruder had SD of 19 mm; L/SD of 20 : 1; a compression ratio (CR) of 3 : 1; and DD of 3 mm. Extrusion cooking at a higher APR and low TD and SS increased TPC. Major phenolic acids in the extrudates were derived from caffeic, salicylic and ferulic acid (Table 2).

**Corn-based snacks containing kañiwa and lupine.** Kañiwa and lupine are gluten-free sources of protein and fibre. Kañiwa (*Chenopodium pallidicaule*) is typically high in protein, minerals and other nutrients (Jan et al. 2017). White lupin (*Lupinus albus* L.), yellow lupin (*L. luteus* L.) and narrow-leafed lupin (*L. angustifolius* L.) can be an alternative to soya beans (Palanisamy et al. 2019). Ramos Diaz et al. (2017) investigated the effects of various contents of kañiwa or lupine (*Lupinus angustifolius*) flour on physical and chemical properties of extruded snacks. A twin-screw laboratory extruder (Thermo Prism PTW24 Thermo; Haake, Germany) comprised seven sections with the individual temperature (90–140 °C) control in six of them. The total length of the screw and SD were 672 and 24 mm, respectively. The screws consisted of six conveying areas, five mixing areas, one transition element and one extrusion element. FR was maintained at 86 g $min^{-1}$. Grain type (kañiwa or lupine), the content of kañiwa or lupine flour (20–50% of solids), TD (140–160 °C), SS (200–500 rpm) and water content of the mixture (14–18%) as well as protein, ash, fibre content and the main fatty acids of the blend were the predictors in the PLSR model. TPC in extrudates was comparable to that of unprocessed flour blends. Increasing TD had an overall proportional effect on TPC in the extrudates containing 20% kañiwa or lupine, calculated after acid hydrolysis. The extrudates containing 20% kañiwa or lupine presented losses of phenolic compounds of approximately 45% percentage points (relative to the flour blend), but at higher contents of kañiwa or lupine, the loss of phenolic compounds was reduced considerably, to around 20% percentage points. The extrudates containing either kañiwa or lupine showed an overall increase in TPC (after acid-hydrolysis treatment) after extrusion.

**Extrusion of the mixture containing corn grits and ground kale.** Kasprzak et al. (2018) processed blends of corn grits and ground dried kale in blends containing 2, 4, 6, and 8% of kale, respectively. The samples were conditioned to 15% FM by spraying with water and mixing continuously for 10 min. The blends were processed in a TS-45 single screw extruder-cooker with L/SD = 12. In the corn snacks enriched with kale, fifteen phenolic acids were indicated by high-performance liquid chromatography-electrospray ionisation tandem (quadrupole time-of-flight) mass spectrometry (Table 2). Both the qualitative and quantitative contents of polyphenols increased with the addition of kale.

**Extrusion of the mixture containing corn grits and carrot pulp.** Ortak et al. (2017) processed feed samples prepared by adding carrot pulp to corn grits at a ratio of 1 : 4 to the final moisture content of 25.34%. They used a laboratory scale twin-screw co-rotating extruder (Feza Machine Co. Ltd., Istanbul, Turkey) with DD and L/SD 3 mm and 25 : 1, respectively. SS was set at 125 rpm or 225 rpm and two temperature regimes were applied. Change in the extrusion parameters, temperature and SS did not affect the TPC (Table 1) and antioxidant activity significantly within the studied range.

**Extrusion of the mixture containing corn and Moldavian dragonhead leaves.** The Moldavian dragonhead (*Dracocephalum moldavica* L., *Lamiaceae*) is an annual, herbaceous plant with unique nutritional characteristics. It is a good source of protein, lipids and fibre. Dragonhead seeds are useful for the extraction of oil rich in omega-3 fatty acids. It has been confirmed as a good source of linolenic acid. There are some reports showing the application of *Dracocephalum moldavica* as tea used to treat stomach and liver disorders, headaches and congestion. Wojtowicz et al. (2017) evaluated the application of Moldavian dragonhead leaves replacing corn in extruded snacks. They used a single screw extruder-cooker type TS-45 with L/SD 12 : 1; the screw CR was 3 : 1. The barrel zone temperatures were set at 125, 145, and 135 °C during the experiment, and SS was set at 120 rpm. Ready-to-eat snacks (crisps) were shaped with a circular die of 3 mm and cut directly after exciting the forming die with a rotary cutting knife. The presence of phenolic compounds in the extrudates, especially rosmarinic acid (Table 2), showed a high antioxidant potential.

**Extrusion of the mixture containing genetically modified corn and bean kernels.** Rascón-Cruz et al. (2004) expressed the main seed storage protein of amaranth (Amarantin) in the kernel of common corn to obtain a transgenic corn with increased amounts of lysine (+18%) and tryptophan (+22%). Recombinant

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Amarantin expressed in corn kernels was digested by simulated gastric fluid treatment. Amarantin transgenic corn is not an allergenicity inducer (Sinagawa-García et al. 2004). Espinoza-Moreno et al. (2016) processed this genetically modified corn and black bean kernels by extrusion cooking in a single-screw laboratory extruder Model 20 DN (CW Brabender Instruments, USA) with 19 mm SD, L/SD of 20 : 1, 3 : 1 CR, and 3 mm DD. Extrusion conditions were selected as follows: FM (15–25%), barrel temperature (120–170 °C) and SS (50–240 rpm). The extrusion process increased free, bound and total phenolic content by 88.9, 74.0 and 74.3%, respectively. High increase of TPC (Table 1) during the extrusion process may be due to the destruction of cell walls and the release of phenolic compounds, as well as Maillard reaction products quantified as phenolics.

**Extrusion of the mixture containing corn and freeze-dried red and purple potatoes.** Red and purple potatoes have recently gained the interest of food producers, as they are a source of active polyphenols. Gumul et al. (2018) analysed the content of phenolic acids in the range of 25–73 mg 100 g$^{-1}$ DS in extrudates with a varying share of freeze-dried red and purple potatoes. She found the highest content of total flavonols compared to other authors (Table 3) and total flavonoid content in the range of 47 206 mg 100 g$^{-1}$ DS. Extrusion was performed by a Brabender 20 DN single-screw extruder having SS 190 rpm, DD 3 mm, CR 1 : 2, temperature profile 150, 165, and 180 °C, and FM 13%. Application of a 25% share of freeze-dried red potatoes of the Magenta Love variety to the extrudates proved to be the best in terms of the content of bioactive compounds and antioxidant activity.

**Corn-based snacks containing amaranth and quinoa.** Amaranth and quinoa are gluten-free alternatives. Additionally, both possess high quality protein (albumin and globulin), a high amount of dietary fibre and substantial quantities of bioactive compounds such as phenolic compounds, tocopherols and folate. Ramos Diaz et al. (2017) studied the effects of amaranth and quinoa supplements and parameters of the extrusion cooking on the physical properties and chemical composition of corn-based extrudates. Content of amaranth or quinoa flour (20–50% of solids of the blend), TD (140–160 °C), SS (200–500 rpm), water content of the mixture (14–18%) as well as the contents of protein, ash, dietary fibre and main fatty acids of the blend were the predictors in the PLSR and L-PLSR. The water content of the mixture and SS were of the distinctly greatest importance for physical response variables such as torque and pressure at the die during extrusion, sectional expansion index, stiffness and water content of the extrudates. Those containing amaranth showed an increase in TPC (between 6 and 15 percentage points relative to the flour blend after acid-hydrolysis treatment) while those containing quinoa showed a reduction in TPC (between 1 and 9 percentage points relative to the flour blend after acid hydrolysis).

**Extrusion of corn and buckwheat flour.** Several studies revealed a high content of amino acids, phenolic acids, rutin, quercetin, isoquercetin, kaempherol in different parts of common and Tartary buckwheat and thus found buckwheat to be a functional food (Jiang et al. 2015). Some bioactive compounds of Tartary buckwheat can decrease the glucose level in blood. Additionally, some scientific studies also demonstrated some antibacterial and anti-inflammatory properties. Due to the high content of antioxidants, numerous minerals and nutritional components, buckwheat is cultivated for seeds. Singh et al. (2019) dealt with the characteristics of corn grit extrudates containing buckwheat flour at various levels (0, 10, 20 and 30% w/w). The extrusion process was done on an extruder having two screws (BC 21; Clextral, France) which were intermeshing and co-rotating. The barrel diameter was 0.025 m and L/SD ratio was 16 : 1. The extrusion machine was equipped with four barrel heating zones having temperatures kept constant at 40, 100, and 100 °C. However, the temperature of the fourth zone (die area) was set at 130, 150, or 170 °C. Buckwheat incorporation at different levels increased phenolic content (Table 1).

## EXTRUSION BASED ON CASSAVA FLOURS

**Extrusion of the mixture containing cassava flour and tigernut flour.** High-quality cassava flour (HQCF) is an unfermented, smooth, odourless, white or creamy flour with no gluten. Tigernut tubers are rich in fibre, protein and natural sugars, and minerals (Belewu & Belewu 2007). Tigernut flour has a distinct sweet taste; it is gluten-free. Adebowale et al. (2017) investigated the composition of extruded snacks produced from different blends of HQCF and tigernut flour. The snacks were produced using a single-screw laboratory extruder at constant FM (27%), SS (60 rpm) and barrel temperature (80 °C). The used screw L/SD, SD and screw length were 16.43 : 1, 18.5 mm and 304 mm, respectively. A flat die of 15 mm width was used to produce non-expanded extrudates. TPC of all the flour blends significantly increased with tigernut flour inclusion (Table 1).

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Table 3. Flavonols in extrudates from chosen mixtures

| Phenolic compound | Source | Source input (raw material) (mg 100 $g^{-1}$ DS) | Output (extrudates) (mg 100 $g^{-1}$ DS) | Retention (%) | Extruder | Author |
|---|---|---|---|---|---|---|
| Quercetin-O-pentoside | Rice/beans/ carob fruit | ND–22 | ND–3.4 | 0–31 | twin-screw | Arribas et al. (2019) |
| Total flavonols | Corn/ purple potato | – | 18–24 | – | single-screw | Gumul et al. (2018) |
| Total flavonols | Corn/ red potato | – | 17–33 | – | single-screw | Gumul et al. (2018) |
| Catechin hexoside | Lentil flour with yeast | 33–66 | 2–6 | 5–9 | co-rotating twin-screw | Ciudad-Mulero et al. (2018) |
| Kaempferol-O-desoxyhexoside-O-hexoside-O-rutinoside | Lentil flour with yeast | 1–3 | 0.4–0.6 | 13–34 | co-rotating twin-screw | Ciudad-Mulero et al. (2018) |
| Quercetin-3-O-glucoside | Lentil flour with yeast | 4–5 | 0.4–0.6 | 8–11 | co-rotating twin-screw | Ciudad-Mulero et al. (2018) |
| Quercetin-O-hexoside | Lentil flour with yeast | 3–4 | 0.3–0.5 | 10–12 | co-rotating twin-screw | Ciudad-Mulero et al. (2018) |
| Quercetin-O-pentoside | Lentil flour with yeast | 5–6 | 0.5–0.8 | 8–12 | co-rotating twin-screw | Ciudad-Mulero et al. (2018) |
| Total flavonols | Lentil flour with yeast | 15–17 | 2 | 12–13 | co-rotating twin-screw | Ciudad-Mulero et al. (2018) |

ND – not detected

**Extruded cassava-soy composite with grape pomace.** Grape pomace is a by-product of wine production. It is used in animal feed and as fertiliser. The phenolic compounds are mainly condensed tannins, anthocyanins, and resveratrol (Ahmedna 2013). Oladiran and Emmambux (2018) prepared a cassava-soy composite with grape pomace at 0, 10 and 20% addition levels by a co-rotating twin screw extruder with five heating zones set at 60, 80, 100, 140, and140 °C. A moisture dosing rate of 3 L $h^{-1}$ and FR of 25 kg $h^{-1}$ were used with DD of 3 mm. SS was maintained at 200 rpm. Some nutritional, functional and rheological properties, TPC Table 1), and antioxidant activity of the products were analysed.

## EXTRUSION BASED ON LENTIL FLOUR

**Extrusion of the mixture containing lentil flour and yeast.** Lentils are a good source of proteins and carbohydrates. The low glycaemic response and high fibre content of lentils help to control body weight by increasing the feeling of satiety (Rathod & Annapure 2017). Ciudad-Mulero et al. (2018) used a Clextral EVOL HT32-H twin-screw extruder with co-rotating and intermeshing screws (SD 32 mm; L/SD ratio 24, 500 rpm, 50 kg $h^{-1}$). The extruder was equipped with six sections. They evaluated the differences in the analysed phenolic compounds between the raw and the extruded (140 and 160 °C) formulation. A decrease in TPC (Table 1) and in the content of individual phenolic compounds analysed using the Dionex Ultimate 3000 UPLC (Thermo Scientific, San Jose, CA, USA) simultaneously with a DAD (280 and 370 nm) and in a mass spectrometer (Linear Ion Trap LTQ XL mass spectrometer, Thermo Finnigan, San Jose, CA, USA) operating in negative mode (Table 3) were related to the temperature. In the samples without yeast extruded at 160 °C, an extended decrease in the TPC content was observed compared with the non-extruded sample, which was higher than in the sample extruded at 140 °C.

**Extrusion of the mixture containing lentil flour and orange peel powder.** Citrus fruits are a rich source of phenolic compounds. Orange peel remains after juice extraction and has about 50–70% of fresh fruit weight. It is a waste with little economic value. It can help the extruded product to have high consumer acceptability in the market by highlighting the mouthfeel and texture. The study of Rathod & Annapure (2017) investigated the effects of the extrusion processing

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parameters on TPC, total flavonoid content and antioxidant activity of the lentil-orange peel powder blend. The blend of lentil flour and orange peel powder was extruded in a co-rotating twin-screw extruder (KETSE 20/40 Brabender, Duisburg, Germany) with four independent heating zones. DD was 4 mm and FR was kept constant at 16 rpm (20.4 kg $h^{-1}$). Extrudates were produced using temperatures in the range of 130–170 °C and three levels of SS (150, 200, and 250 rpm). Temperatures for the zones were as follows: 85, 105, and 125 °C for the conveying zone; 100, 120, and 140 °C for the mixing zone; 115, 135, and 155 °C for the cooking zone; and (die) 130, 150, and 170 °C for the high-pressure zone. TPC retention of the extruded product was 70–86% and the values of TPC of the product are the highest ones in Table 1. Therefore, the blend has a huge potential to produce extrudates with good acceptance.

## OTHER APPLICATIONS

**Extrusion of the mixture containing wheat flour (WF) and artichoke leaf powder (ALP).** The artichoke (*Cynara scolymus* L.) has an antioxidative and hepatoprotective potential due to phenolic substances composed of especially mono- and dicaffeoylquinic acids and flavonoids (Fratianni et al. 2007). Guven et al. (2018) prepared samples with weight ratios of 0 : 100, 3 : 97, 6 : 94 and 9 : 91 ALP to WF on dry basis. FM was adjusted to 19.7%. FR, SS and DD of a co-rotating twin screw extruder (Feza Machine Co., Istanbul, Turkey) were approximately 55 g $min^{-1}$, 250 rpm and 3.0 mm, respectively. Barrel temperature zones were set at 80 °C, 90 °C, 130 °C and 150 °C (die: 128 °C). Although extrusion had a destructive effect on TPC (Table 1: 65–77% of the phenolic content of raw mixtures were retained after the extrusion process), *in vitro* bioaccessibility of bioactive molecules was higher after the extrusion process. ALP addition significantly increased total phenolic content. The extrusion process caused a decrease in cynarin and cynaroside contents (Table 2).

**Extrusion of sorghum and roasted coffee blends.** Coffee contains many compounds such as phenolic compounds, minerals, and dietary fibre. Chávez et al. (2017) extruded roasted coffee powder (KP) in whole grain sorghum flours of two genotypes in two water content conditions, and the variations of TPC (Table 1) and phenolic acids were investigated as well as the functional properties. The mixtures were extruded using a single-screw extruder 19/20 DN (Brabender, Duisburg, Germany) equipped with a screw (3 : 1), DD of 3 mm, operating at SS of 180 rpm and FR adjusted by a volumetric feeder corresponding to an average of 4.0 ± 0.9 kg $h^{-1}$, fitted to a torque rheometer DCE330 (Brabender, Duisburg, Germany). The barrel temperature profile of the three heating zones was kept constant at 60, 120, and 140 °C, respectively. Increasing KP and moisture led to a reduction of expansion. TPC decreased in sorghum depending on the genotype (10 and 40%) after extrusion, whereas in mixtures with KP, TPC increased (Table 1).

**Preparation of meat analogues based on *Spirulina*/lupin protein mixtures.** *Spirulina* belongs to the most dominant microalgal species of commercial importance. Although *Spirulina* contains many nutrients, the high protein concentration is of particular interest for the development of protein-rich foods. Palanisamy et al. (2019) studied the effect of the addition of *Spirulina platensis* flour to lupin protein mixtures. The hot melt extrusion (HME) process was performed using a Coperion ZSK 27 Mv PLUS twin-screw extruder (Coperion GmbH, Stuttgart, Germany). At first the *Spirulina* biomass was mixed with the lupin protein mixture (lupin concentrate and lupin isolate) and iota carrageenan. The authors tested texture, cooking yield, expressible moisture, and TPC (Table 1); they found total flavonoid content in the range of 77–183 mg 100 $g^{-1}$ DS, measured Trolox equivalent, *in vitro* protein digestibility and conformational changes of proteins using FTIR.

**Polymer-mediated soybean nanocomposite by hot melt extrusion.** Soybeans (*Glycine max* L.) are a source of phenolic acids and flavonoids such as isoflavones, glycosides genistin and daidzin that have a limited distribution in nature. Isoflavones protect the body from cancer, cardiovascular diseases, and osteoporosis. Azad et al. (2019) prepared a soybean food composite (SFC) by an STS-25HS twin-screw HME (Hankook E.M. Ltd., Pyoung Taek, Korea) from hydrophilic food-grade hydroxypropyl methylcellulose and soybeans. The HME extruder was equipped with a round-shaped die (1 mm) at a feeding rate of 40 g $min^{-1}$ at 150 rpm, with a high shear of the twin screw. The processing temperature of HME was fixed at 80 °C and 130 °C. TPC (Table 1), flavonoids and single isoflavone content – including daidzin, daidzein, glycitein, genistein, and genistin – were significantly increased in the mixture at 130 °C compared to the control.

**Textured vegetable protein influenced by extrusion cooking and green tea contents.** Green tea contains polyphenols (25–35%), polysaccharides (20–25%), protein (25–30%) and 26 kinds of amino acids, more than 50 mineral elements and vitamins, and other functional ingredients. Green tea has antioxidant, antibacterial, anticarcinogenic, antiviral, antiaging, and

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antimutagenic functions. Ma and Ryu (2019) extruded a mixture by a co-rotating intermeshing twin-screw extruder (THK 31T, Incheon Machinery, South Korea) with a screw length of 690 mm and L/SD of 23 : 1. The extrusion parameters were fixed as follows: 140 °C barrel temperature, 50% FM, 200 rpm SS, 100 g $min^{-1}$ FR. Increasing the amount of green tea resulted in higher TPC (Table 1); they found the high total flavonoid content in the range of 2 688–4 985 mg 100 $g^{-1}$ DS, and they also tested catechin and caffeine content. On the other hand, it is a little surprising that the results of flavonoids in the extrudates were higher than TPC.

## CONCLUSION

Although it is well known that short-time processing by extrusion gives a potential advantage for retaining phenolics compared to other heating treatments, the papers show new possibilities for research in this area. Fruits are a primary source of dietary phenolic compounds; phenolics and antioxidant activity of extrudates are positively correlated with their addition into the starchy source. Many scientific papers deal with total phenolic compounds, their composition and amount of components (e.g., phenolic acids, isoflavones and flavonoids). Besides the high content of phenolics, the primary requirement for a food producer is to have a sensorially acceptable product; therefore, technological and technical settings of one-screw or twin-screw cooking extrusion are also provided in this review.

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